IN-38
9103
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NASA Contractor Report 195332

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May 1994

Prepared for
Lewis Research Center
Under Contract NAS3–27186

National Aeronautics and
Space Administration

(NASA-CR-195332) EVALUATION OF PYROLYSIS AND ARC TRACKING ON CANDIDATE WIRE INSULATION DESIGNS FOR SPACE APPLICATIONS Final Report (NYMA) 7 p

N94-32901

Unclas

G3/38 0009103

Evaluation of Pyrolysis and Arc Tracking on Candidate Wire Insulation Designs for Space Applications.

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ABSTRACT

Polyimide wire insulation has been found to be vulnerable to pyrolization and arc tracking due to momentary short-circuit arcing events. This report compares arc tracking susceptibility of candidate insulation configurations for space wiring applications. The insulation types studied in this report were gauge 20 (0.81mm dia.) hybrid wiring constructions using polyimide, tetrafluoroethylene (TFE), cross-linked ethylene tetrafluoroethylene (XL-ETFE) and/or polytetrafluoroethylene (PTFE) insulations. These constructions were manufactured according to military wiring standards for aerospace applications. Arc track testing was conducted under DC bias and vacuum (10^{-6} torr). The tests were conducted to compare the various insulation constructions in terms of their resistance to arc tracking restrike. The results of the tests are presented.

INTRODUCTION

To insure proper operation of spacecraft; the wiring systems must be capable of meeting the electrical, thermal, mechanical, chemical, and operational requirements associated with space applications [1]. Failure to do so may result in the loss of both mission and lives.

Polyimide insulation is commonly used in space wiring applications because of its high dielectric strength, low weight, nonflammability, tolerance to high temperature, and high abrasion resistance [1]. However, polyimide insulation, such as MIL-W-81381, has been found to be vulnerable to pyrolization and arc tracking when momentary short-circuit arcs have occurred on aircraft power systems [2,3]. A momentary short-circuit arc between conductors may induce enough localized heating to thermally char (pyrolize) the polyimide wiring insulation. This charred polyimide can be conductive and capable of sustaining the short-circuit arc. Sustained arcing may allow propagation along the wire bundle through continuous pyrolization of the polyimide insulation (arc tracking). Since the pyrolized insulation is not necessarily a direct short circuit, circuit breakers and/or in-line-fuses may not always trip due to arc tracking [4]. If a circuit breaker does trip, the arc tracking may restart when the circuit breaker is reset (restrike). Furthermore, an arc involving one pair of wires in a multiple wire bundle may thermally char an adjoining pair of wires within that bundle (flashover), ultimately leading to complete failure of the entire wire bundle.

Due to the potential losses from an arc tracking event, finding an insulation construction that will not arc track is desirable. However, all the space application insulation construction types tested to date are susceptible, with varying degrees, to arc tracking. Therefore, a program was developed in an effort to compare the different insulation constructions as per their arc tracking resistance. The tests conducted and the results obtained are discussed in this paper.

APPARATUS

Tests were conducted on the Abraded Circuit Experiment (ACE) bell-jar which provides a helium cryo-pumped vacuum of $5x10^{-6}$ torr. The ACE facility is equipped with three Sorenson power supplies: two DCR 300-6Bs (300 volts, 6 amps) and a DCR 300-9B (300 volts, 9 amps). The availability of three separate power supplies makes possible the energizing of three independent wire pair circuits within a bundle. This feature is necessary for conducting flashover tests; however, for conducting the arc tracking tests described in this paper, only one wire pair was energized.

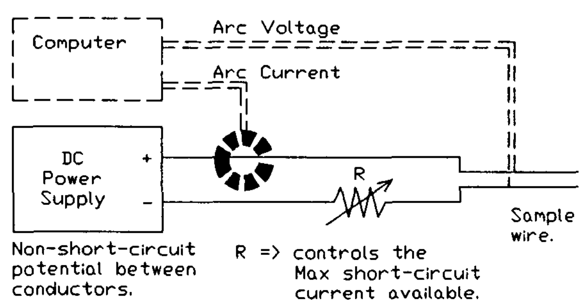

Figure 1. Typical circuit configuration for an arc tracking test.

A typical circuit configuration for an arc tracking test is described in Figure 1. The circuit's power supply voltage level is adjustable for setting the non-short-circuit potential between the conductors of a wire pair. The circuit's current-limiting resistor is selected by the operator to restrict the maximum short-circuit current available during an arcing event.

Each wire bundle used for these arc tracking tests consisted of a single twisted pair of wires. These wire bundles were suspended from terminal strips inside the vacuum bell-jar as described in Figure 2. A platform within the bell-jar, capable of being raised and lowered by the operator, is located under the suspended wire bundles. On the platform is an aluminum cup, electrically connected to the wire pair's return line, positioned directly below the suspended wire bundle. When the platform is raised (position B in Figure 2), the wire pair's supply line end will touch the side of the cup. The momentary touching of the supply line wire on the aluminum cup temporarily introduces a direct short-circuit at the wire end.

SAMPLE DESCRIPTION

Each sample prepared for these arc tracking tests consisted of two wires--a supply line and a return line with the same

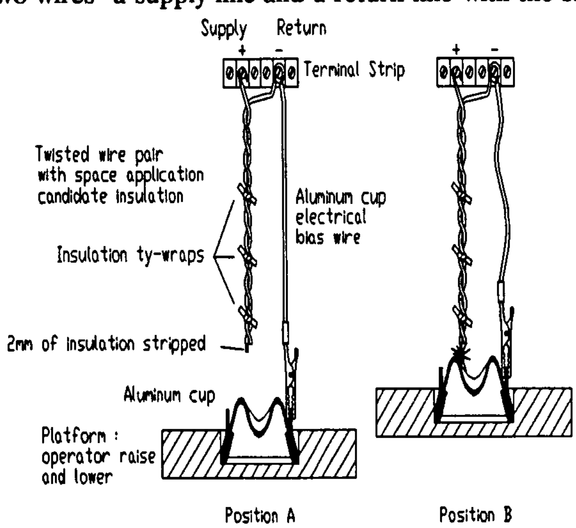

Figure 2. Arc tracking sample mount.

insulation type. To maintain the wires within close proximity to each other throughout the test, conductorless insulation--same insulation type as the sample--was wrapped around the sample at discrete intervals of 2.5 cm. One end of the supply line had 2mm of insulation stripped off the wire conductor, while the return line's insulation went all the way to the end of the conductor. With this configuration, the insulation material was in close proximity to arcs created between the supply line tip and the aluminum cup.

The three AWG 20 (American Wiring Gauge 20) samples tested were manufactured by Champlain, Filotex, and Teledyne Thermatics. These insulations were hybrid constructions comprised of different combinations of the materials PTFE, TFE, polyimide, and XL-ETFE. Detailed descriptions of these constructions are given in reference 5. The Filotex and Thermatics (#3) samples were among the top 4 insulation configurations identified by an Air Force wiring program [5]. The Champlain (#1) construction is another hybrid insulation which has been proposed for aerospace use.

PROCEDURE

The tests performed included both arc tracking initiation and arc restrike under 5×10^{-6} torr. The data reported in this paper concern arc tracking restrike tests. Before a restrike test can be conducted, the arc tracking event must be manually initiated on the wire sample. This was accomplished by raising and lowering the platform until the energized sample wire pair experienced enough direct short-circuits with the aluminum cup, that the insulation was pyrolized to the point where arc tracking was self sustaining. At this point, the power supplies were turned off, the power supply voltage setpoint was set to 0V, and the test sample was ready for the arc tracking restrike tests.

The arc tracking restrike tests were carried out to ascertain the minimal voltage necessary to sustain an arc on the wire sample, for each current limiter. Therefore, the voltage was incremented from 0 volts (open circuit power supply voltage) until the arc tracking restarted (restrike). After the arc tracking restarted, the power supply was turned off to terminate the arcing. At this point, the final open circuit power supply voltage and the employed current limiter value were noted. Also, the potential short circuit current was calculated using Ohm's law:

$$I_{sc} = \frac{V_{oc}}{R_{lim}}$$

where I_{sc} is the potential short circuit current, V_{oc} is the open circuit power supply voltage, and R_{lim} is the employed current limiter. The volt x amp product (VAP)--V_{oc} multiplied by the I_{sc} value--was also used as an instrument of comparison between insulation types.

RESULTS

Figures 3, 4, and 5 display the arc tracking data points obtained from these tests. Each data point represents the open-circuit-voltage (OCV) plotted against the calculated potential short-circuit-current (PSCC) obtained from a single arc tracking restrike test. The data in Table 1 displays the minimal OCV and PSCC necessary for restrike. Figure 6's plot compares the samples ability to withstand restrike with respect to VAP. The minimum VAPs for each insulation type are also displayed in Table 1.

Table 1. Minimal open-circuit-voltage (OCV), minimal potential short-circuit-current (PSCC), and minimum volt-amp-product (VAP) necessary for restrike.

Insulation Type	Minimum OCV (Volts)	Minimum PSCC (Amps)	Minimum VAP (V x A)
Champlain	48.0	0.9	54.0
Filotex	52.0	0.7	57.2
Teledyne Thermatics	28.0	0.7	36.4

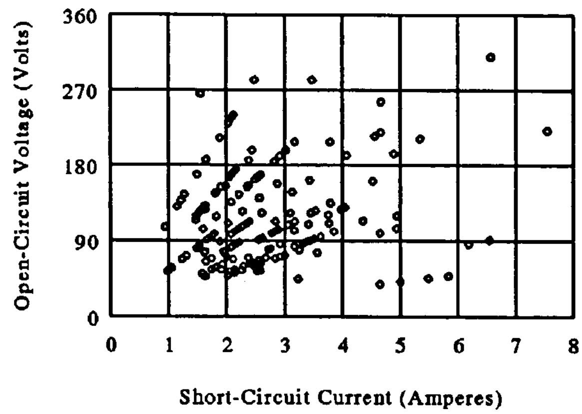

Figure 3. Champlain Arc Tracking Restrike test results.

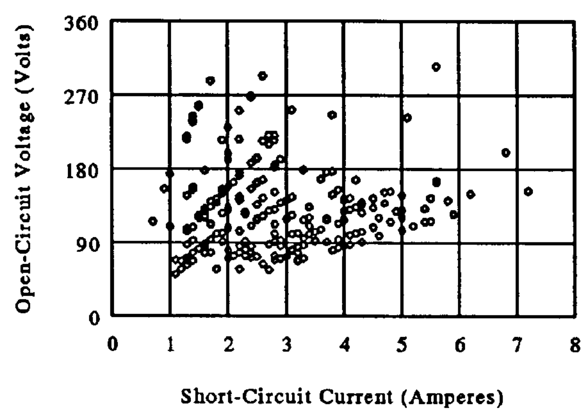

Figure 4. Filotex Arc Tracking Restrike test results.

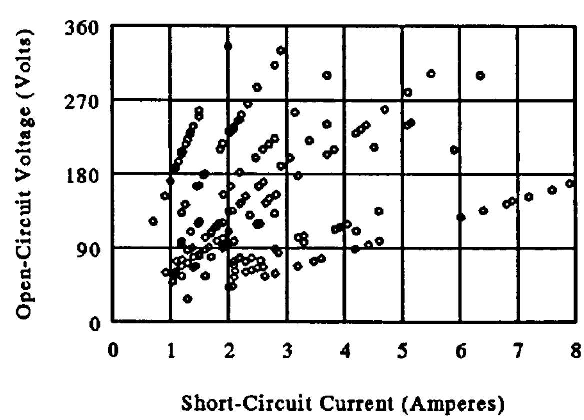

Figure 5. Teledyne Thermatics Arc Tracking Restrike test results.

DISCUSSION

The arc tracking restrike phenomenon can be explained as follows: After the arc tracking event has been initiated and extinguished by removing power, a partial hexagonal, graphitic carbon residue may remain between the conductors [2]. These partial carbon traces may not necessarily provide a flawless conductive medium between the conductors; gaps may exist in the carbon trace. These gaps may prevent current flow during the restrike test for low voltage differences between conductors. As this voltage increases, the electric field strength may exceed the dielectric strength of the carbon/gap medium, resulting in current flow. This applied voltage difference between conductors, necessary to break down the carbon/gap dielectric, may be dependent upon how the carbon traces lie. Due to the explosive nature of the arcing event, the positioning of the conductive carbon traces will be unpredictable. This random positioning of carbon traces may produce a variable dielectric strength for the carbon/gap medium, resulting in an inconsistent minimal OCV for the restrike tests. The carbon/gap media, not being a direct short-circuit between conductors, may simulate a resistive load between the conductors; therefore, a wire protection device (fuse, circuit breaker, etc.) may not necessarily trip while arc tracking exists. Once dielectric breakdown occurs, the current flow through the carbon/gap medium will generate heat due to i^2R Joule heating, where i is the current and R is the resistance of the carbon/gap medium. If the i^2R power is high enough to continue pyrolizing the polyimide, the arc tracking will be sustained; else, the arc tracking event will extinguish. Since a high enough OCV is necessary to break down the carbon/gap medium, the minimal OCV necessary to restart the arc tracking event may be considered a determining factor describing the susceptibility of the insulation to restrike. Furthermore, since the level of current flow generating the i^2R heating must be high enough to sustain the arc tracking event once it has been started, the available current for the arc to conduct may also be a determining factor for considering the susceptibility of polyimide arc restrike. Finally, the minimal VAP necessary to sustain the arc may be a determining factor for identifying the material most resistant to arc tracking.

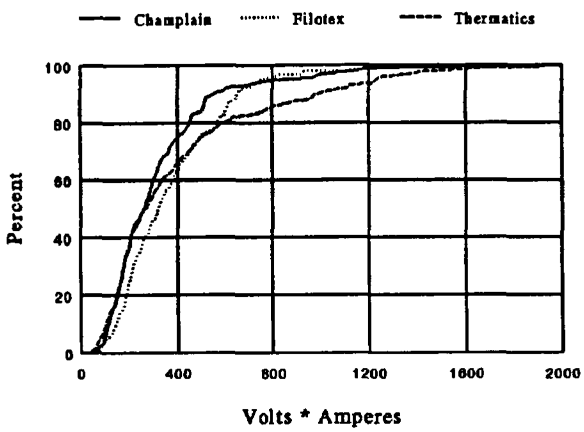

Figure 6. Percentage of restrike tests that restarted arc tracking for less than a given VAP.

For each of the three insulation samples studied in this paper, the minimal PSCC values were indistinguishable. The minimal OCV and VAP values necessary for restrike favored the Champlain and Filotex insulation types. However, these criteria for comparison are based only on a single data point and do not provide a substantial difference in determining the superior material for resisting restrikes on charred polyimide wire.

Figure 6 displays the percentage of data points that arc tracked at or below a given volt amp product. The better insulation types--having higher volt amp product values before arc tracking--are farther to the right. Therefore, Figure 6 identifies the Filotex insulation construction as the least susceptible to arc tracking restrike of the three insulation types.

The statistical data, for all three sample types, are given in Table 2 for the volt amp product values displayed in Figure 6. By comparing the mean value of each insulation type's VAP, the Teledyne Thermatics appears the most resistant to arc tracking and the Filotex is second best. To validate this premise, a hypothesis test is in order to determine if there exists a statistical difference between the mean values of the following pairs: Champlain and Teledyne Thermatics, Champlain and Filotex, and Teledyne Thermatics and Filotex. Let l_j represent the true average VAP necessary for restrike to occur on the j^{th} insulation type. Therefore, the null hypotheses H_0: $l_1 - l_2$] 0 will be compared against the alternative hypothesis H_a: $l_1 - l_2 = 0$ using the equation given below for Z. H_0 is rejected if either Z > 1.29 or Z < -1.29 which corresponds to a type I error

$$Z = \frac{X - Y}{\sqrt{\frac{\sigma_1^2}{m} + \frac{\sigma_2^2}{n}}}$$

Table 2. Volt amp product statistical data for arc tracking requirements.

VAP	Insulation Type: Champlain	Teledyne Thermatics	Filotex
Mean	328.18	412.81	377.61
Standard Deviation	275.44	381.64	244.63
Number of Tests	173	178	258
Standard Error	20.94	28.60	15.23
95% Confidence	41.05	56.07	29.85
99% Confidence	54.03	73.80	39.29

probability of a = .2. A type I error consists of rejecting H_0 when H_0 is true. In the equation for Z: X and Y are the sample set means, r_1 and r_2 are standard deviations, and m and n are the number of tests conducted. The comparison between the Champlain and Teledyne Thermatics resulted in a Z of 2.89. Since 2.89 > 1.29, H_0 is accepted in favor of the conclusion $l_{Champlain}$] $l_{Teledyne\ Thermatics}$. The comparison between the Champlain and Filotex resulted in a Z of 1.91. Since 1.91 > 1.29, H_0 is accepted in favor of the conclusion $l_{Champlain}$] $l_{Filotex}$. The comparison between the Filotex and Teledyne Thermatics resulted in a Z of 1.08. Since 1.08 < 1.29, H_0 is rejected in favor of the conclusion $l_{Filotex} = l_{Teledyne\ Thermatics}$. Statistically, there is no difference between the Filotex mean and the Teledyne Thermatics mean. However, there are differences between the Champlain and Filotex means and the Champlain and Teledyne Thermatics means. Therefore, to statistically make a decision between the Teledyne Thermatics and the Filotex, further testing is necessary. Based on the available data, both the Filotex and Teledyne Thermatics insulation materials are considered statistically better than the Champlain because the Champlain has the lowest VAP mean of the three.

Arc tracking, at power levels discussed in this paper, did not always initiate at the onset of the very first momentary short circuit. Typically, several momentary short circuits were necessary before the insulation was pyrolized enough to propagate an arc. However, the number of momentary short circuits necessary for arc tracking initiation was dependent on the intensity of the arcs associated with each momentary short-circuiting exercise. By quantifying each arc's intensity and summing all the intensities leading up to arc track initiation, an energy value may be correlated with the arc tracking initiation, for a given insulation type. Each arc's intensity may be quantified by the integration (with respect to time) of the voltage and current product. This type of information may be useful in determining which type of insulation is least likely to start arc tracking if a wire conductor, with damaged insulation, were to generate momentary arcs.

CONCLUSIONS

The goal was to identify an insulation material immune to arc tracking. Unfortunately, all three candidate space application insulation construction types tested to date are capable of arc tracking. The five methods used for comparing arc track restrike resistance were: minimal PSCC (all three candidates were indistinguishable), minimal OCV (Filotex at 52V and Champlain at 48V were higher than Teledyne Thermatics' 28V), minimal VAP (Filotex at 57.2 and Champlain at 54 were higher than Teledyne Thermatics' 36.4), Figure 6's comparison of the medians (At the lower percentiles, Filotex had the highest VAPs), and Table 2's statistical comparison (Filotex's and Teledyne Thermatics' mean VAPs were higher than Champlain's). Champlain's only argument towards consideration (good minimum VAP and OCV) are based on a single data point. A stronger argument, considering all the data, favors the Filotex and Teledyne Thermatics. Further testing is necessary to distinguish a difference between these two insulation materials resistance to arc tracking restrike. Future tests may determine arc tracking susceptibility by measuring the energy level necessary to initiate the arc tracking event. Further testing is also necessary to deter mine the level of joule heating necessary to initiate and propagate the pyrolization of the insulation material, which is associated with the arc tracking event.

ACKNOWLEDGEMENTS

This work was supported by NASA Lewis Research Center, contract # NAS3-27186.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	May 1994	Final Contractor Report

4. TITLE AND SUBTITLE

Evaluation of Pyrolysis and Arc Tracking on Candidate Wire Insulation Designs for Space Applications

5. FUNDING NUMBERS

WU-323-57-4A
C-NAS3-27186

6. AUTHOR(S)

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

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8. PERFORMING ORGANIZATION REPORT NUMBER

E-8849

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135-3191

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA CR-195332

11. SUPPLEMENTARY NOTES

Thomas J. Stueber, Ahmad Hammoud, and Mark W. Stavnes, NYMA, Inc., Engineering Services Division, Brook Park, Ohio 44142 (work funded by NASA Contract NAS3-27186); Kenneth Hrovat, Cleveland State University, Cleveland, Ohio 44115. Project Manager, John Dickman, Power Technology Division, organization code 5430, NASA Lewis Research Center, (216) 433-6150.

12a. DISTRIBUTION/AVAILABILITY STATEMENT	12b. DISTRIBUTION CODE
Unclassified - Unlimited Subject Category 38	

13. ABSTRACT *(Maximum 200 words)*

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14. SUBJECT TERMS	15. NUMBER OF PAGES
Wiring constructions; Insulation; Arc tracking	7
	16. PRICE CODE
	A02

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	